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Nonlinear roll damping of a barge with and without liquid cargo in spherical tanks

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Abstract

Damping plays a significant role on the maximum amplitude of a vessel's roll motion, in particular near the resonant frequency. It is a common practice to predict roll damping using a linear radiation–diffraction code and add that to a linearized viscous damping component, which can be obtained through empirical, semi-empirical equations or free decay tests in calm water. However, it is evident that the viscous roll damping is nonlinear with roll velocity and amplitude. Nonlinear liquid cargo motions inside cargo tanks also contribute to roll damping, which when ignored impedes the accurate prediction of maximum roll motions. In this study, a series of free decay model tests is conducted on a barge-like vessel with two spherical tanks, which allows a better understanding of the nonlinear roll damping components considering the effects of the liquid cargo motion. To examine the effects of the cargo motion on the damping levels, a nonlinear model is adopted to calculate the damping coefficients. The liquid cargo motion is observed to affect both the linear and the quadratic components of the roll damping. The flow memory effect on the roll damping is also studied. The nonlinear damping coefficients of the vessel with liquid cargo motions in spherical tanks are obtained, which are expected to contribute in configurations involving spherical tanks.

Keywords: LNG carrier; Nonlinear roll damping; Liquid cargo motion; Spherical tanks; Model test.

1. Introduction

Floating Liquefied Natural Gas (FLNG) [21] is a new floating-structure concept which combines upstream facilities for liquefying natural gas at -162 ºC, storage of the liquefied gas in cargo tanks and offloading it into LNG Carriers. Side-by-side offloading has been identified as a promising configuration between LNG Carriers and the FLNG vessel for offtake of LNG. In this concept, LNG carriers that would normally be berthed against a jetty on the coast, or in ports with break waters, are now required to lift cargo in the open seas. Due to the close proximity between FLNG and the LNG carrier and the weathervaning capability of the FLNG, the operation is sensitive to the roll motions of the two vessels. The carrier roll motions may, as a consequence, dominate the availability in some regions. A reliable prediction of the roll response of LNG carriers is therefore important.

Extensive studies on this problem have been conducted during the past decades. For roll motions of a small amplitude, a linear formulation can provide more or less reliable predictions (Blagoveshchenskiĭ [1]; Salvesen et al. [13]). However, as the response amplitude becomes large, nonlinearities become significant, necessitating a nonlinear formulation [2]. One possible nonlinear contribution could be accounted for by introducing nonlinear restoring coefficients [5] that are dependent on the shape of the stability diagram [16]. However, it is unable to match completely with experimental data by solely considering nonlinear restoring moments (Denise [5]; Robinson and Stoddart [12]). To achieve a complete match, viscous damping needs to be included. In contrast, nonlinear restoring force seems not necessary when the nonlinear damping effects have been accounted for. As a consequence, it is therefore essential to better understand the damping levels for a reliable prediction of the roll motions of a vessel.

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To predict the viscous damping of roll motions, Tanaka [15] developed a semi-empirical method. Following that, Ikeda et al. [8] conducted a comprehensive series of experimental studies. In their study, they divided the roll damping into several components and developed a method for predicting the roll damping. Each component is predicted theoretically if possible, otherwise empirically. 26 years later, Ikeda [9] improved his empirical formula to be able to determine the damping coefficients for ships considering forward speed. In addition, Chakrabarti [4] examined the roll damping components and explained the empirical formulas for various types of roll damping, which are helpful for prediction of roll damping. For engineering purposes, the roll motion of a floating structure can be predicted more or less reliably using semi-empirical and empirical methods [6]. It should be noted that this does not mean the roll motion problem has been solved. In contrast, more research is necessary in this area [7].

To the authors' knowledge, all existing studies focus on the viscous damping associated with the outer hull of a floating structure or ship without free-surface effects. In other words, the possible effect of liquid cargo motions inside tanks has not been considered. However, the liquid cargo motions may play a significant role in the roll damping, which further affects the operational window for side-by-side offloading of FLNG facilities. It is of significant value, therefore, to examine the roll damping contributions from the liquid cargo motions and to understand better the roll damping level by incorporating a contribution from the liquid cargo motions inside tanks.

In this study, a series of experiments are carried out with a vessel model fitted with spherical tanks. Several roll-decay tests have been performed. The tanks are filled with water to represent partially-filled conditions. To identify the effects of the liquid cargo motion on the roll damping level, additional sets of runs were performed for which the tanks were empty, but the vessel properties modified to result in a 'frozen' approximation of the partially-filled condition. To provide a basis for numerical simulations, we demonstrate the roll damping levels of the vessel in various partially-filled conditions. The memory effect of liquid flow is studied through free decay tests with different initial exciting amplitudes.

2. Theoretical background

Assuming that there is no coupling from motions at other degrees of freedom, a typical roll motion equation considering nonlinear roll damping can be written as follows [3,14,16,18]:

$$(M+A)\ddot{\varphi} + B_L\dot{\varphi} + B_N\dot{\varphi}|\dot{\varphi}| + K\varphi = M(t), \tag{1}$$

where φ, $\dot{\varphi}$, and $\ddot{\varphi}$ are the roll angle, angular velocity, and angular acceleration. $M$and A refer to the displacement and added mass moments of inertia in roll. K is the restoring coefficient and $M(t)$ is the exciting moment by external force, which equals zero in a free decay test in calm water. B_L and B_N represent the linear and quadratic damping coefficients, respectively.

2.1. Linear damping model

The non-dimensional equation of the roll motion for the free decay tests considering solely linear damping can be written as:

$$\ddot{\varphi} + 2\xi\omega_n\dot{\varphi} + \omega_n^2\varphi = 0, \tag{2}$$

where ξ is the ratio of linear damping B_L to critical damping $B_{crit} = 2\cdot\sqrt{(M+A)\cdot K}$, and ω_n is the natural frequency of the roll motion, which can be expressed as $\omega_n = \sqrt{K/(M+A)}$.

A general solution for Eq. (2) can be written in the following form:

$$\varphi(t) = e^{-\xi\omega_n t}(k_1\cos\omega_d t + k_2\sin\omega_d t), \tag{3}$$

where k_1 and k_2 are constants, which can be determined by initial conditions. ω_d is the damped natural frequency of the oscillations in water (including the damping effects). ω_d can be expressed through:

$$\omega_d = \omega_n\sqrt{1-\xi^2}. \tag{4}$$

Defining the interval between two successive peaks (or troughs) as the natural period, T_n, of the oscillations and substituting Eq. (4) into Eq. (3), one can obtain the relationship between the values of two subsequent peaks in the decaying motion signal through the following equation:

$$\frac{\varphi_i}{\varphi_{i+1}} = e^{\xi\omega_n\frac{T_n}{2}} = e^{\xi\pi}, \tag{5}$$

where φ_i and φ_{i+1} are the motion amplitudes of the i^{th} and $(i+1)^{th}$oscillations. The non-dimensional damping coefficient can therefore be expressed as the following equation:

$$\xi = \frac{1}{\pi}\frac{\ln\varphi_i - \ln\varphi_{i+N}}{N}, \tag{6}$$

where N is the number of oscillations. Based on Eq. (6), the variations of damping coefficients with respect to the roll response amplitudes can be easily plotted. To distinguish with the following one, the damping coefficient obtained by this approach is referred to as classical damping [19].

2.2. Nonlinear damping model

To evaluate the nonlinear damping term B_N in the roll motion Eq. (1), it is assumed [3,10] that the decaying oscillation is reasonably harmonic over each half cycle. Therefore, the nonlinear term is linearized by a Fourier series expansion as:

$$\dot{\varphi}|\dot{\varphi}| = \frac{8}{3\pi}\omega_n\varphi_i\dot{\varphi}, \tag{7}$$

As a consequence, the non-dimensional nonlinear equitation of roll motion can be written as:

$$\ddot{\varphi} + 2\zeta\omega_n\dot{\varphi} + \eta\frac{8}{3\pi}\omega_n\varphi_i\dot{\varphi} + \omega_n^2\varphi = 0, \tag{8}$$

where η is the non-dimensional form of the nonlinear term B_N $(\eta = B_N/(M+A))$.